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Fast fault detection scheme for series-compensated lines during power swing

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ABSTRACT

This paper reports the use of a novel ultra-high speed scheme to release the distance relay to operate for a fault during a power swing in the series compensated line. In the scheme, in order to extract the fault induced voltage and current components, voltage and current samples are analyzed by the multi-resolution morphological gradient (MMG), first. Then, the fault initiated forward travelling wave is computed at the distance relay point. Next, Likelihood ratio [LR] test is utilized to detect a jump in the statistical mean of the calculated forward travelling wave. Finally, a support vector machine (SVM) classifier is employed to distinguish faults from other normal capacitor and switching transients. It is shown that in all of the simulated cases, our ultra-high speed algorithm was successful in fault detection across a wide range conditions including, fault type, fault resistance, fault location, pre-fault loading and fault inception time. Moreover, we found that using the proposed scheme significantly speeded the fault detection, in comparison with the existing phasor based methods. In addition, the improvements noted in our algorithm are achieved with a low computational burden.

1. Introduction

The performance of distance relays during a power swing has received much attention in recent years due to its vital role to prevent further propagation of disturbances. Disturbances such as power system faults, the loss of a large generation and the heavily loaded line tripping lead to oscillations of rotor angles of synchronous machines in an interconnected power system. These oscillations result in severe power swings. During these power swings, the impedance seen by a distance relay may enter in one or more of distance relay protecting zones. That may cause the false tripping, as a result of which is an exacerbation of the power system disturbance. Hence, a power swing block (PSB) function is used in most modern relays to prevent the unwanted distance relay element operation during a power swing [1,2]. On the other hand, the distance relay should be unblocked and allowed to trip when a fault occurs during a power swing.

There is an extensive literature on the fault detection during a power swing. Mechraoui and Thomas proposed a scheme based on the phase angle of the voltage phasor to detect unbalance faults [3,4]. The issue of the three phase fault detection has also been addressed by many researchers; Benmouyal et al. introduced an algorithm based on the swing center voltage (SCV) and its rate [5], Lotfifard et al. investigated the use of the magnitude of the DC decaying component of the current signal [6], Brahma shown the capability of time-frequency based features to detect balance faults [7], Gautam et al. applied the mathematical morphology (MM) tool to design a current based algorithm [8], Lin et al. examined the change rate of the active and reactive power [9], Mahamedi et al. employed the fundamental frequency component of the instantaneous active power [10], Pang et al. presented an ultra-high speed scheme according to the information of the initiated travelling waves during faults [11] and Nilesh et al. suggested an intelligent algorithm based on the support vector machine (SVM) classifier [12]. In 2013 Nayak et al. addressed the fault detection problem during a power swing in series compensated lines and provided a phasor based scheme using the negative sequence component of the current signal and the cumulative sum (CUSUM) tool [13], Roy et al. developed this further and established a fault detection, classification and location scheme [14]. More recently, Dubey et al. used the phase spaced method to detect a symmetrical fault during a power swing [15], Swetapadma et al. proposed a scheme based on decision tree for the fault detection and the faulted phase(s) identification [16], and Khodaparast et al. presented an algorithm based on transient monitor for the three phase fault detection [17]. However, although the fault

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detection during a power swing in series compensated lines was demonstrated using the phasor based schemes over three years ago, little attention has been paid to solve this problem using ultra-high speed schemes.

The present paper presents a set of travelling wave based criteria for detecting such faults. On the basis of these criteria it then illustrates the preparation of a new ultra-high speed scheme. This scheme can rapidly detect faults during a power swing in the series compensated lines, within 2 ms.

This article was collected in eight parts as follows: Section 2 briefly describes the theoretical basis of the proposed scheme that include transient travelling waves, multi-resolution morphological gradient, likelihood ratio test and support vector machine classifier. Section 3 presents the preparation of the proposed scheme to detect fault during power swing. Sections 4 and 5 present the system modeling and results, respectively. Application of the proposed algorithm to WSCC 3-machine 9-bus system is reported in Section 6. Section 7 gives a comparative assessment of the presented scheme. Finally, conclusions are expressed in Section 8.

2. Theoretical basis

As mentioned earlier, although the problem of the fault detection during a power swing in the series compensated line, was solved using phasor based algorithms over three years ago [13,14], little attention has been paid to employ the travelling wave based algorithms. The travelling waves content a valuable information for detecting a fault in a transmission line. According to this information, many schemes were provided to the transmission line protection [18,26–28]. In this paper, a set of forward travelling wave based criteria was presented. On the basis of these criteria, the preparation of an ultra-high speed fault detection algorithm was then described.

The forward travelling wave can be calculated using the induced fault voltage and current components. In the proposed algorithm, the multi-resolution morphological gradient tool [19] was employed to extract the fault injected voltage and current components. Moreover, Likelihood ratio test [20] was utilized to detect a jump in the statistical mean parameter of the calculated forward travelling wave. Finally, the support vector machine classifier [29] was used for distinguishing faults from capacitor and load switching transients.

2.1. Travelling waves

Any sudden change in parameters of a transmission line including driving sources and/or configuration results in occurrence of transient phenomena. One of the main causes of transients in transmission lines are faults. When a fault occurs at a point of a transmission line, traveling waves including forward traveling wave and backward traveling wave are created and going in opposite directions along the transmission line. The fault induced voltage and current components are expressed, based on the forward traveling wave u^{+} and the backward traveling wave u^{-} as the following [21]:

$$\Delta u(x,t) = u^{+}(x - vt) + u^{-}(x + vt) \tag{1}$$

$$\Delta i(x,t) = \frac{1}{Z_C}[u^{+}(x - vt) - u^{-}(x + vt)] \tag{2}$$

where Δu and Δi are the fault induced of voltage and current components, respectively. Moreover, v and Z_C are the propagation velocity of traveling wave and the characteristic impedance of the transmission line, respectively, and are calculated as the following [21]:

$$v = \frac{1}{\sqrt{L_0 C_0}} \tag{3}$$

$$Z_C = \sqrt{\frac{L_0}{C_0}} \tag{4}$$

where L_0 and C_0 are the inductance and the capacitance of the transmission line in per unit, respectively. Using (1) and (2) the forward traveling wave u^{+} and the backward traveling wave u^{-} are computed as follows [21]:

$$u^{+} = \frac{1}{2}(\Delta u + Z_C \Delta i) \tag{5}$$

$$u^{-} = \frac{1}{2}(\Delta u - Z_C \Delta i) \tag{6}$$

In our study, during the power swing condition in the series compensated line, the statistical information of the forward travelling wave was used to detect an occurred fault.

2.2. Multi-resolution morphological gradient

The mathematical morphology (MM) is a powerful tool for signal analysis in time domain. In contrast to conventional signal processing techniques such as Fourier transform (FT) and wavelet transform (WT), the MM has a little computational burden [19]. Basic arithmetic operators used in MM include addition, subtraction, maximum and minimum, only. Hence, the method is fast and simple to implement on existing processors.

The basic words of the morphological literature are dilation and erosion which are defined as follows, respectively [19]:

$$(f \oplus g)(x) = \max_{s}\{f(x+s) + g(s) | (x+s) \in D_f, s \in D_g\} \tag{7}$$

$$(f \ominus g)(x) = \max_{s}\{f(x+s) - g(s) | (x+s) \in D_f, s \in D_g\} \tag{8}$$

where f and g are the input signal and the structure element (SE), respectively. Moreover, D_f and Dg are the domains of f and g, respectively. In fact, the dilation uses expansion process and the erosion uses shrinking process for an input signal.

The morphology gradient (MG) aims at extracting the signal gradient, which is a powerful tool for edge detection problems. Mathematically, this gradient is the arithmetic difference between the dilation and the erosion of a signal through an SE and is defined by [19]:

$$G(f) = (f \oplus g) - (f \ominus g) \tag{9}$$

where G is the MG function. In order to improve the MG, the multi-resolution morphological gradient (MMG) is introduced in [19]. Employing the MMG tool, the differential analysis of a signal is possible. The MMG is implemented through the following steps [19],

step (1) ρ^{a}_{g+} and ρ^{a}_{g-} which denote the ascending and descending edges of a signal, respectively, are extracted by

$$\rho^{a}_{g+} = (\rho^{a-1} \oplus g^{+})(x) - (\rho^{a-1} \ominus g^{+})(x) \tag{10}$$

$$\rho^{a}_{g-} = (\rho^{a-1} \ominus g^{-})(x) - (\rho^{a-1} \oplus g^{-})(x) \tag{11}$$

where

$$g^{+} = \{0_1, 0_2, \ldots, \underline{0_{l_a}}\} \tag{12}$$

$$g^{-} = \{\underline{0_1}, 0_2, \ldots, 0_{l_a}\} \tag{13}$$

while $l_a = 2^{a-1} l_g$. The variables a and l_g indicate the level of MMG and the primary length of g at the first level, respectively. Moreover,